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Article 1

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The Importance of Imperviousness

The emerging field of urban watershed protection often lacks a unifying theme to guide the efforts of its many participants—planners, engineers, landscape architects, scientists, and local officials. The lack of a common theme has often made it difficult to achieve a consistent result at either the individual development site or cumulatively, at the watershed scale.

In this article a unifying theme is proposed based on a physically defined unit: imperviousness. Imperviousness here is defined as the sum of roads, parking lots, sidewalks, rooftops, and other impermeable surfaces of the urban landscape. This variable can be easily measured at all scales of development, as the percentage of area that is not "green."

Imperviousness is a very useful indicator with which to measure the impacts of land development on aquatic systems. Reviewed here is the scientific evidence that relates imperviousness to specific changes in the hydrology, habitat structure, water quality and biodiversity of aquatic systems. This research, conducted in many geographic areas, concentrating on many different variables, and employing widely different methods, has yielded a surprisingly similar conclusion: stream degradation occurs at relatively low levels of imperviousness (~10%). Most importantly, imperviousness is one of the few variables that can be explicitly quantified, managed and controlled at each stage of land development. The remainder of this article details the relationship between imperviousness and stream quality.

The Components of Imperviousness

Imperviousness represents the imprint of land development on the landscape. It is composed of two primary components: the *rooftops* under which we live, work and shop, and the *transport* system (roads, driveways, and parking lots) that we use to get from one roof to another. As it happens, the transport component now often exceeds the rooftop component in terms of total impervious area created. For example, transport-related imperviousness comprised 63 to 70% of total impervious cover at the site in 11 residential, multifamily and commercial areas where it had actually been measured (City of Olympia, 1994b). This phenomenon is observed most often in suburban areas and reflects the recent ascendancy of the automobile in both our culture and landscape. The sharp increases in per capita vehicle ownership, trips taken, and miles travelled have forced local planners to increase the relative size of the transport component of imperviousness over the last two decades.

Traditional zoning has strongly emphasized and regulated the first component (rooftops) and largely neglected the transport component. While the rooftop component is largely fixed in zoning, the transport component is not. As an example, nearly all zoning codes set the maximum density for an area, based on dwelling units or rooftops. Thus, in a given area, no more than one single family home can be located on each acre of land, and so forth.

Thus, a wide range in impervious cover is often seen for the same zoning category. For example, impervious area associated with medium density single family homes can range from 20% to nearly 50%, depending on the layout of streets and parking. This suggests that significant opportunities exist to reduce the share of imperviousness from the transport component.

Imperviousness and Runoff

The relationship between imperviousness and runoff may be widely understood, but it is not always fully appreciated. Figure 1 illustrates the increase in the site runoff coefficient as a result of site impervious cover, developed from over 40 runoff monitoring sites across the nation. The runoff coefficient ranges from zero to one and expresses the fraction of rainfall volume that is actually converted into storm runoff volume. As can be seen, the runoff coefficient closely tracks percent impervious cover, except at low levels where soils and slope factors become more important. In practical terms, this means that the total runoff volume for a one-acre parking lot (Rv = 0.95) is about 16 times that produced by an undeveloped meadow (Rv = 0.06).

To put this in more understandable terms, consider the runoff from a one-inch rainstorm (see Table 1). The total runoff from a one-acre meadow would fill a standard size office to a depth of about two feet (218 cubic feet). By way of comparison, if that same acre was completely paved, a one-inch rainstorm would completely fill your office, as well as the *two* next to it. The peak discharge, velocity and time of concentration of stormwater runoff also exhibit a striking increase after a meadow is replaced by a parking lot (Table 1).

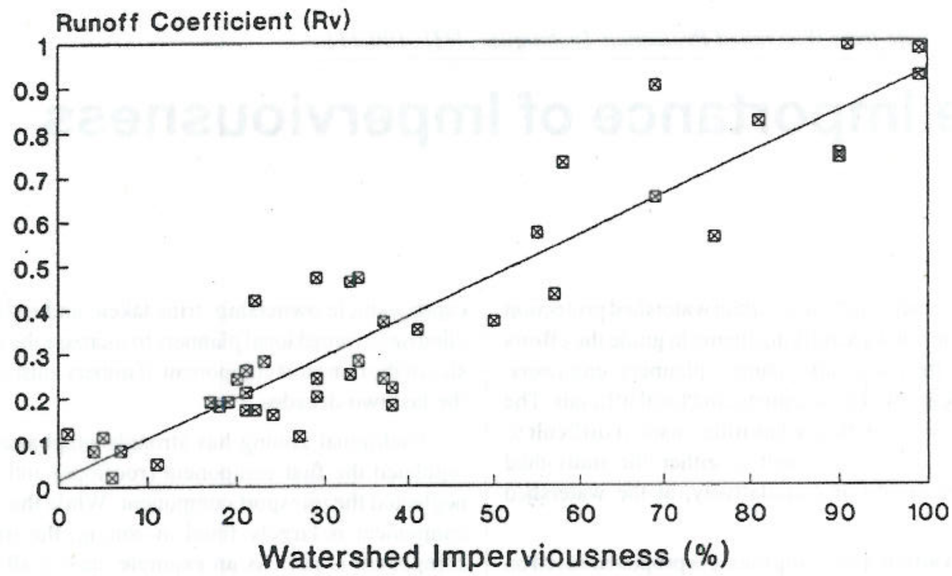


Figure 1: Watershed Imperviousness and the Storm Runoff Coefficient

Because infiltration is reduced in impervious areas, one would expect groundwater recharge to be proportionately reduced. This, in turn, should translate into lower dry weather stream flows. Actual data, however, that demonstrate this effect is rare. Indeed, Evett *et al.* (1994) could not find any statistical difference in low stream flow between urban and rural watersheds after analyzing 16 North Carolina watersheds. Simmons and Reynolds (1982) did note that dry weather flows dropped 20 to 85% after development in several urban watersheds in Long Island, New York.

It should be noted that transport-related imperviousness often exerts a greater hydrological impact than the rooftop-related imperviousness. In residential areas, runoff from rooftops can be spread out over pervious areas, such as backyards, and rooftops are not always directly connected to the storm drain system. This may allow for additional infiltration of runoff. Roads and parking lots, on the other hand, are usually directly connected to the storm drain system.

Table 1: Comparison of One Acre of Parking Lot Versus One Acre of Meadow in Good Condition

Runoff or Water Quality Parameter	Parking Lot	Meadow
Curve number (CN)	98	58
Runoff coefficient	0.95	0.06
Time of concentration (minutes)	4.8	14.4
Peak discharge rate (cfs), 2 yr., 24 hr. storm	4.3	0.4
Peak discharge rate (cfs), 100 yr. storm	12.6	3.1
Runoff volume from one-inch storm (cubic feet)	3450	218
Runoff velocity @ 2 yr. storm (feet/second)	8	1.8
Annual phosphorus load (lbs/ac./yr.).	2	0.50
Annual nitrogen load (lbs/ac./yr.).	15.4	2.0
Annual zinc load (lbs/ac./yr.)	0.30	ND

Key Assumptions:
Parking lot is 100% impervious with 3% slope, 200 feet flow length, Type 2 Storm, 2 yr. 24 hr. storm = 3.1 inches, 100 yr. storm = 8.9 inches, hydraulic radius = 0.3, concrete channel, and suburban Washington 'C' values.
Meadow is 1% impervious with 3% slope, 200 foot flow length, good vegetative condition, B soils, and earthen channel.

Imperviousness and the Shape of Streams

Confronted by more severe and more frequent floods, stream channels must respond. They typically do so by increasing their cross-sectional area to accommodate the higher flows. This is done either through widening of the stream banks, downcutting of the stream bed, or frequently, both. This phase of channel instability, in turn, triggers a cycle of streambank erosion and habitat degradation.

The critical question is at what level of development does this cycle begin? Recent research models developed in the Pacific Northwest suggest that a threshold for urban stream stability exists at about 10% imperviousness (Booth, 1991; Booth and Reinelt, 1993) (Figure 2). Watershed development beyond this threshold consistently resulted in unstable and eroding channels. The rate and severity of channel instability appears to be a function of sub-bankfull floods, whose frequency can increase by a factor of 10 even at relatively low levels of imperviousness (Hollis, 1975; Macrae and Marsalek, 1992; Schueler, 1987).

A major expression of channel instability is the loss of instream habitat structures, such as the loss of pool and riffle sequences and overhead cover, a reduction in the wetted perimeter of the stream and the like. A number of methods have been developed to measure the structure and quality of instream habitat in recent years (Galli, 1993; Gibson *et al.*, 1993; Plafkin *et al.*, 1989). Where these tools have been applied to urban streams, they have consistently demonstrated that a sharp threshold in habitat quality exists at approximately 10 to 15% imperviousness (Booth and Reinelt, 1993; Galli, 1994; Shaver *et al.*, 1995). Beyond this threshold, urban stream habitat quality is consistently classified as poor.

Imperviousness and Water Quality

Impervious surfaces collect and accumulate pollutants deposited from the atmosphere, leaked from vehicles or derived from other sources. During storms, accumulated pollutants are quickly washed off and rapidly delivered to aquatic systems.

Monitoring and modeling studies have consistently indicated that urban pollutant loads are directly related to watershed imperviousness. Indeed, imperviousness is the key predictive variable in most simulation and empirical models used to estimate pollutant loads. For example, the Simple Method assumes that pollutant loads are a direct function of watershed imperviousness (Schueler, 1987), as imperviousness is the key independent variable in the equation.

Threshold Limits for Maintaining Background Pollutant Loads

Suppose that watershed runoff drains into a lake that is phosphorus-limited. Also assume that the present background load of phosphorus from a rural land use amounts to 0.5 lbs/ac/yr. The Simple Method predicts that the post-development phosphorus load will exceed background loads once watershed imperviousness exceeds 20 to 25% (Figure 3), thereby increasing the risk of nutrient over-enrichment in the lake.

Urban phosphorus loads can be reduced when urban stormwater treatment practices are installed, such as stormwater ponds, wetlands, filters or infiltration practices. Performance monitoring data indicates that stormwater practices can reduce phosphorus loads by as much as 40 to 60%, depending on the practice selected. The impact of this pollutant reduction on the post-development phosphorus loading rate from the site is shown in Figure 3. The net effect is to raise the phosphorus threshold to about 35 to 60% imperviousness, depending on the performance of the stormwater practice installed. Therefore, even when effective practices are widely applied, a threshold of imperviousness is eventually crossed, beyond which predevelopment water quality cannot be maintained.

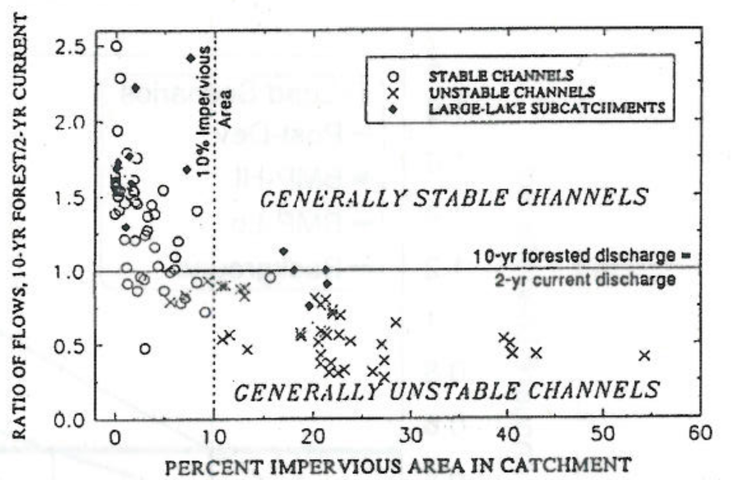


Figure 2: Channel Stability as a Function of Imperviousness (Booth and Reinelt, 1993)

Imperviousness and Stream Warming

Impervious surfaces both absorb and reflect heat. During the summer months, impervious areas can have local air and ground temperatures that are 10 to 12 degrees warmer than the fields and forests that they replace. In addition, the trees that could have provided shade to offset the effects of solar radiation are absent.

Water temperature in headwater streams is strongly influenced by local air temperatures. Galli (1991) reported that stream temperatures throughout the summer are increased in urban watersheds, and the degree of warming appears to be directly related to the impervious cover of the contributing watershed. He monitored five headwater streams in the Maryland Piedmont over a six-month period, each of which had different levels of impervious cover (Figure 4). Each of the urban streams had mean temperatures that were consistently warmer than a forested reference stream, and the size of the increase (referred to as the delta-T) was a direct function of watershed imperviousness. Other factors, such as lack of riparian cover and ponds, were also demonstrated to amplify stream warming, but the primary contributing factor appeared to be watershed impervious cover (Galli, 1991).

Imperviousness and Stream Biodiversity

The health of the aquatic ecosystem is a strong environmental indicator of watershed quality. A number of research studies have recently examined the links between imperviousness and the biological diversity in streams. Some of the key findings are summarized in Table 2.

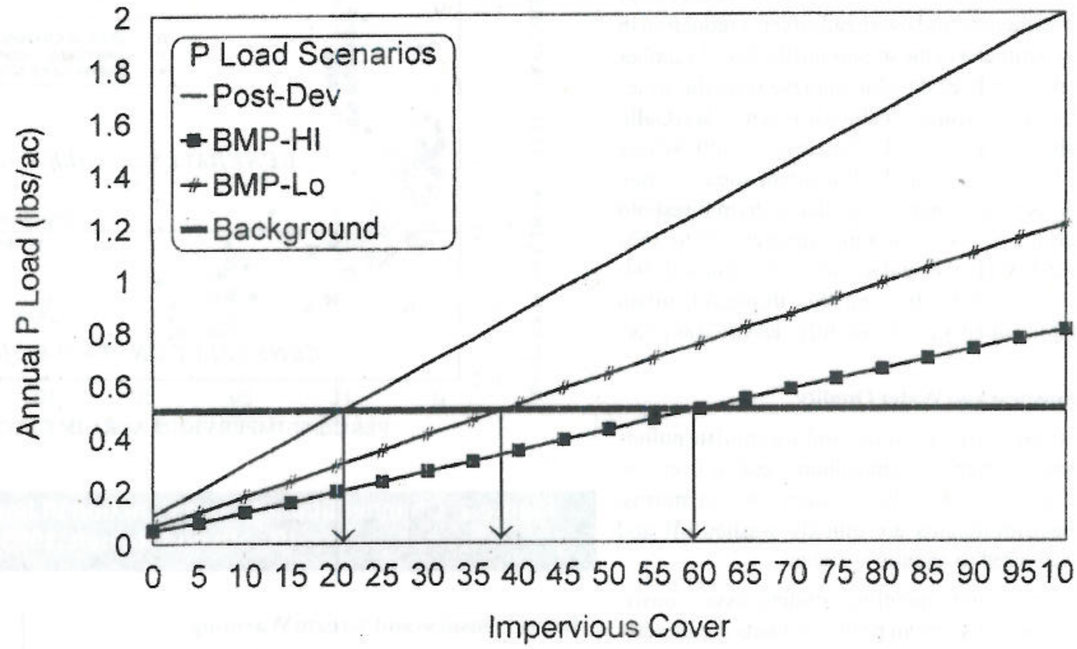
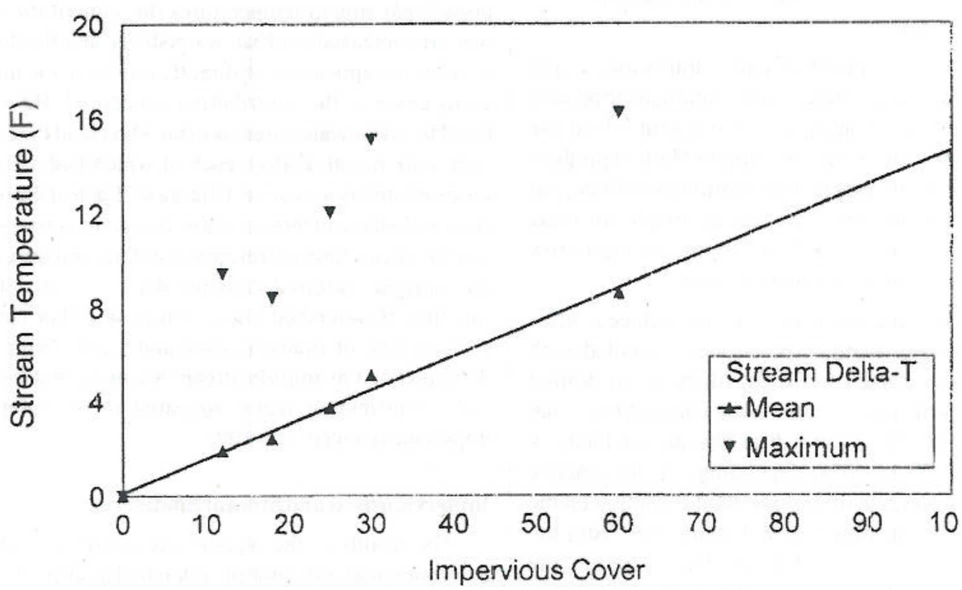
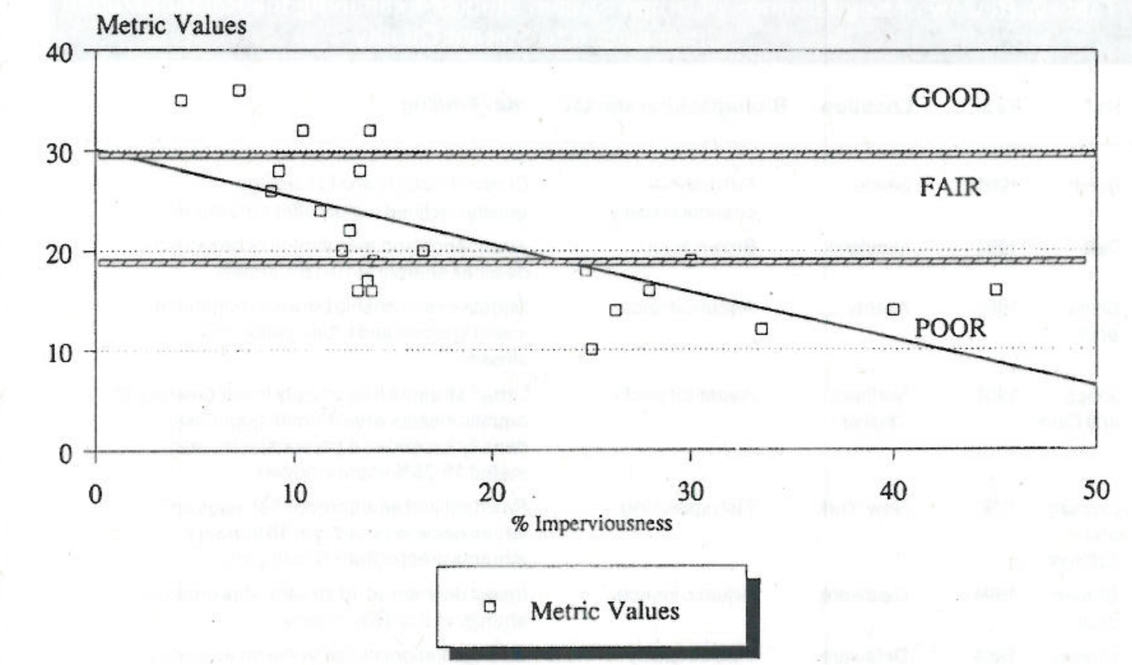


Figure 3: The Effect of Impervious Cover on Urban Phosphorus Load Under Several Scenarios, as Computed by the Simple Method



Delta-t is the difference in mean or max stream temperature from a developed stream, compared to an undisturbed stream.

Figure 4: The Effect of Impervious Cover on Stream Temperature (Galli, 1991)



Metric Values are based upon the sum of scores assigned for the following categories: EPTC balance, EPT Index, Average Generic Diversity, Chironomid Abundance, Taxonomic Richness (Family and Generic)

Figure 5: Impacts of Imperviousness on Macroinvertebrate Communities in the Headwater Streams of the Anacostia River (Schueler and Galli, 1992)

Aquatic Insects

The diversity, richness and composition of the aquatic insect community has frequently been used to evaluate the quality of urban streams. Not only are aquatic insects a useful environmental indicator, but they also form the base of the stream food chain in most regions of the country.

Klein (1979) was one of the first to note that macroinvertebrate diversity drops sharply in urban streams in Maryland. Diversity consistently became poor when watershed imperviousness exceeded 10 to 15%. The same basic threshold has been reported by all other research studies that have looked at macroinvertebrate diversity in urban streams (Table 2).

In each study, sensitive macroinvertebrates were replaced by ones that were more tolerant of pollution and hydrologic stress. Species such as stoneflies, mayflies, and caddisflies largely disappeared and were replaced by chironomids, tubificid worms, amphipods, and snails. Species that employ specialized feeding strategies—shredding leaf litter, grazing rock surfaces, filtering organic matter that flows by, or preying on other insects—were lost.

A typical example of the relationship between imperviousness and macroinvertebrate diversity is shown in Figure 5. The graph summarizes diversity trends for 23 sampling stations in headwater streams of the Anacostia watershed (Schueler and Galli, 1992). While good to fair diversity was noted in all headwater streams with less than 10% impervious cover, nearly all stations with 12% or more impervious cover recorded poor diversity. The same sharp drop in macroinvertebrate diversity at around 12 to 15% impervious cover was also observed in streams in the coastal plain and piedmont of Delaware (Shaver *et al.,* 1995).

Other studies have utilized other indicators to measure the impacts of urbanization on stream insect communities. For example, Jones and Clark (1987) monitored 22 stations in Northern Virginia and concluded that aquatic insect diversity composition changed markedly after watershed population density exceeded four or more individuals per acre. This population density roughly translates to half-acre or one acre lot residential use, or perhaps 10 to 15% imperviousness.

Steedman (1988) evaluated 208 Ontario stream sites, and concluded that aquatic insect diversity shifted from fair to poor at about 35% urban land use. Since "urban land" includes both pervious and impervious cover, the actual threshold in the Ontario study may well be closer to seven to 10% imperviousness (Booth and Reinelt, 1993). Steedman also reported that urban streams with intact riparian forests had higher diversity than those that did not, for the same level of urbanization.

While the exact point at which stream insect diversity shifts from fair to poor is not known with absolute precision, it is clear that few, if any, urban streams can

Table 2: Review of Key Findings of Urban Stream Studies Examining the Relationship of Urbanization to Stream Quality

Ref.	Year	Location	Biological Parameter	Key Finding
Booth	1991	Seattle	Fish habitat/ channel stability	Channel stability and fish habitat quality declined rapidly after 10% imperv.
Galli	1994	Maryland	Brown trout	Abundance and recruitment of brown trout declines sharply at 10-15% imperv.
Benke *et al.*	1981	Atlanta	Aquatic insects	Negative relationship between number of insect species and urbanization in 21 streams
Jones and Clark	1987	Northern Virginia	Aquatic insects	Urban streams had sharply lower diversity of aquatic insects when human population density exceeded 4 persons/acre. (estimated 15-25% imperv. cover)
Limburg and Schimdt	1990	New York	Fish spawning	Resident and anadromous fish eggs and larvae declined sharply in 16 tributary streams greater than 10% imperv.
Shaver *et al.*	1994	Delaware	Aquatic insects	Insect diversity at 19 stream sites dropped sharply at 8 to 15% imperv.
Shaver *et al.*	1994	Delaware	Habitat quality	Strong relationship between insect diversity and habitat quality; majority of 53 urban streams had poor habitat
Schueler and Galli	1992	Maryland	Fish	Fish diversity declined sharply with increasing imperv., loss in diversity began at 10-12% imperv.
Schueler and Galli	1992	Maryland	Aquatic insects	Insect diversity metrics in 24 subwatersheds shifted from good to poor over 15% imperv.
Black and Veatch	1994	Maryland	Fish/insects	Fish, insect and habitat scores were all ranked as poor in 5 subwatersheds that were greater than 30% imperv.
Klein	1979	Maryland	Aquatic insects/fish	Macroinvertebrate and fish diversity declines rapidly after 10% imperv.
Luchetti and Fuersteburg	1993	Seattle	Fish	Marked shift from less tolerant coho salmon to more tolerant cutthroat trout populations noted at 10-15% imperv. at 9 sites
Steedman	1988	Ontario	Aquatic insects	Strong negative relationship between biotic integrity and increasing urban land use/ riparian condition at 209 stream sites. Degradation begins at about 10% imperv.
Pedersen and Perkins	1986	Seattle	Aquatic insects	Macroinvertebrate community shifted to chironomid, oligochaetes and amphipod species tolerant of unstable conditions.
Steward	1983	Seattle	Salmon	Marked reduction in coho salmon populations noted at 10-15% imperv. at 9 sites
Taylor	1993	Seattle	Wetland plants/ amphibians	Mean annual water fluctuation was inversely correlated to plant and amphibian density in urban wetlands. Sharp declines noted over 10% imperv.
Garie and McIntosh	1986	New Jersey	Aquatic insects	Drop in insect taxa from 13 to 4 noted in urban streams
Yoder	1991	Ohio	Aquatic insects/ fish	100% of 40 urban sites sampled had fair to very poor index of biotic integrity scores

support diverse aquatic insect communities at moderate to high levels of impervious cover (25% or more). Four different studies (Benke *et al.*, 1981; Black and Veatch, 1994; Booth, 1991; Garie and McIntosh, 1986) all failed to find aquatic insect communities with good or excellent diversity in these highly urban streams.

Fish Surveys

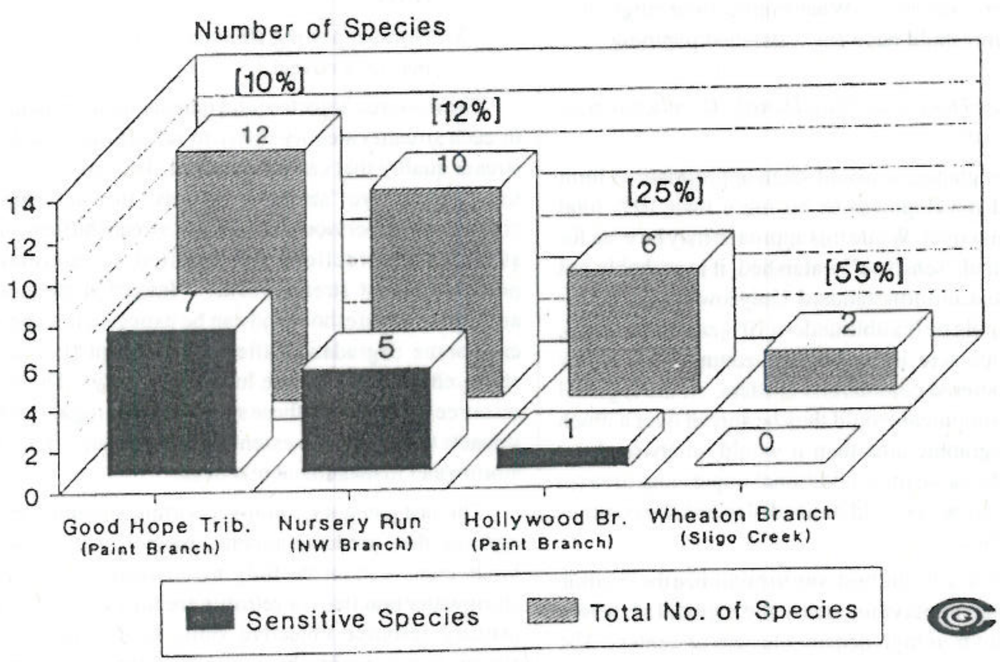
The abundance and diversity of the fish community can also serve as an excellent environmental indicator. Surprisingly, relatively few studies have examined the influence of imperviousness on fish communities in headwater streams. The results of one study are illustrated in Figure 6. Four similar subwatersheds in the Maryland Piedmont were sampled for the number of fish species present. As the level of watershed imperviousness increased, the number of fish species collected dropped. Two sensitive species (trout and sculpin) were lost as imperviousness increased from 10 to 12%, and four more were lost when impervious cover increased to 25%. Significantly, only two species remained in the fish community at 55% imperviousness. Sensitive species, defined as those with a strong dependence on the substrate for feeding and/or spawning, showed a more precipitous decline. Klein (1979) found a similar relationship between fish diversity and watershed impervious cover in several dozen headwater streams in the Maryland Piedmont.

Salmonid fish species (trout and salmon) and anadromous fish species appear to be most negatively impacted by impervious cover. Trout have stringent temperature and habitat requirements, and seldom are present in mid-Atlantic watersheds where imperviousness exceeds 15% (Galli, 1994). Declines in trout spawning success are evident above 10% imperviousness (Galli, 1994). In the Pacific Northwest, Luchetti and Feurstenburg (1993) seldom found sensitive coho salmon in watersheds beyond 10 or 15% imperviousness. Booth and Reinelt (1993) noted that most urban stream reaches had poor quality fish habitat when imperviousness exceeded eight to 12%.

Fish species that migrate from the ocean to spawn in freshwater creeks are also very susceptible to impacts of urbanization such as fish barriers, pollution, flow changes, and other factors. For example, Limburg and Schmidt (1990) discovered that the density of anadromous fish eggs and larvae declined sharply after a 10% imperviousness threshold was surpassed in 16 subwatersheds draining into the Hudson River.

The Influence of Imperviousness on Other Urban Water Resources

Several other studies point to the strong influence of imperviousness on other important aquatic systems such as shellfish beds and wetlands.



Numbers in brackets represent levels of watershed imperviousness.

Sources: 1) MdDNR, 1983 2) MdDNR, 1986 3) ICPRB, 1989

Figure 6: Fish Diversity as a Function of Watershed Imperviousness in Four Subwatersheds in the Maryland Piedmont (Schueler and Galli, 1992)

Even relatively low levels of urban development yield high levels of bacteria, derived from urban runoff or failing septic systems. These consistently high bacterial counts often result in the closure of shellfish beds in coastal waters, and it is not surprising that most closed shellfish beds are in close proximity to urban areas. Indeed, it may be difficult to prevent shellfish closure when more than one septic drain field is present per seven acres—a very low urban density (Duda and Cromartie, 1982). Although it is widely believed that urban runoff accounts for many shellfish bed closures (now that most point sources have been controlled), no systematic attempt has yet been made to relate watershed imperviousness to the extent of shellfish bed closures.

Taylor (1993) examined the effect of watershed development on 19 freshwater wetlands in King County, Washington, and concluded that the additional stormwater contributed to greater annual water level fluctuations (WLF). When the annual WLF exceeded about eight inches, the richness of both the wetland plant and amphibian community dropped sharply. This increase in WLF began to occur consistently when upstream watersheds exceeded 10 to 15% imperviousness.

Implications at the Watershed Level

The many independent lines of research reviewed here converge toward a common conclusion: that it is extremely difficult to maintain predevelopment stream quality when watershed development exceeds 10 to 15% impervious cover. What implications might this apparent threshold have for watershed planning?

Should Low Density or High Density Development be Encouraged?

At first glance, it would seem appropriate to limit watershed development to no more than 10% total impervious cover. While this approach may be wise for an individual "sensitive" watershed, it is probably not practical as a uniform standard. Only low density development would be feasible under a 10% zoning scenario, perhaps one-acre lot residential zoning, with a few widely scattered commercial clusters. At the regional scale, development would thus be spread over a much wider geographic area than it would otherwise have been. At the same time, additional impervious area (in the form of roads) would be needed to link the community together.

Paradoxically, the best way to minimize the creation of additional impervious area at the regional scale is to concentrate it in high density clusters or centers. The corresponding impervious cover in these clusters is expected to be very high (25% to 100%), making it virtually impossible to maintain predevelopment stream quality. A watershed manager must then confront the fact that to save one stream's quality it may be necessary to degrade another.

A second troubling implication of the impervious cover/stream quality relationship involves the large expanses of urban areas that have already been densely developed. Will it be possible to fully restore stream quality in watersheds with high impervious cover? Some early watershed restoration work does suggests that biological diversity in urban streams can be partially restored, but only after extensive stormwater retrofit and habitat structures are installed. For example, fish and macroinvertebrate diversity has been partially restored in one tributary of Sligo Creek, Maryland (Galli, 1994). In other urban watersheds, however, comprehensive watershed restoration may not be feasible, due to a lack of space, feasible sites, or funding.

A Proposed Scheme for Classifying Urban Stream Quality Potential

The thresholds provide a reasonable foundation for classifying the potential stream quality in a watershed based on the ultimate amount of impervious cover. One such scheme is outlined in Table 3. It divides urban streams into three management categories based on the general relationship between impervious cover and stream quality:

1. Sensitive streams (one to 10% impervious cover)
2. Impacted streams (11 to 25% impervious cover)
3. Non-supporting streams (26 to 100% impervious cover)

The resource objective and management strategies in each stream category differ to reflect the potential stream quality that can be achieved. The most protective category are "sensitive streams" in which strict zoning, site impervious restrictions, stream buffers and stormwater practices are applied to maintain predevelopment stream quality. "Impacted streams" are above the threshold and can be expected to experience some degradation after development (i.e., less stable channels and some loss of diversity). The key resource objective for these streams is to mitigate these impacts to the greatest extent possible, using effective stormwater management practices.

The last category, "non-supporting streams," recognizes that predevelopment channel stability and biodiversity cannot be fully maintained, even when stormwater practices or retrofits are fully applied. The primary resource objective shifts to protect downstream water quality by removing urban pollutants. Efforts to protect or restore biological diversity in degraded streams are not abandoned; in some priority subwatersheds, intensive stream restoration techniques

Table 3: A Possible Scheme for Classifying and Managing for Headwater Urban Streams Based on Ultimate Imperviousness

Urban Stream Classification	Sensitive (0-10% Imperv.)	Impacted (11-25% Imperv.)	Non-supporting (26-100% Imperv.)
Channel stability	Stable	Unstable	Highly Unstable
Water quality	Good	Fair	Fair-Poor
Stream biodiversity	Good-Excellent	Fair-Good	Poor
Resource objective	Protect biodiversity and channel stability	Maintain critical elements of stream quality	Minimize downstream pollutant loads
Water quality objectives	Sediment and temperature	Nutrient and metal loads	Control bacteria
Stormwater Practice Selection Factors	Secondary environmental impacts	Removal efficiency	Removal efficiency
Land Use Controls	Watershed-wide imp. cover limits (ICLs), site ICLs	Site imp. cover limits (ICLs)	Additional infill and redevelopment encouraged
Monitoring and enforcement	GIS monitoring of imp. cover, biomonitoring	Same as "Stressed"	Pollutant load modeling
Development rights	Transferred out	None	Transferred in
Riparian buffers	Widest buffer network	Average bufferwidth	Greenways

are employed to attempt to partially restore some aspects of stream quality. In other subwatersheds, however, new development (and impervious cover) is encouraged to protect other sensitive or impacted streams.

Watershed-Based Zoning

Watershed-based zoning is based on the premise that impervious cover is a superior measure for gauging the impacts of growth, compared to population density, dwelling units or other factors. The key steps in watershed-based zoning are as follows: *First*, a community undertakes a comprehensive physical, chemical and biological monitoring program to asses the current quality of its entire inventory of streams. The data are used to identify the most sensitive stream systems and to refine impervious/stream quality relationships. *Next*, existing impervious cover is measured and mapped at the subwatershed level. Projections of future impervious cover due to forecasted growth are also made at this time.

The *third* step involves designating the future stream quality for each subwatershed based on some adaptation of the urban stream classification scheme presented earlier. The existing land use master plan is then modified to ensure that future growth (and impervious cover) is consistent with the designated stream classification for each subwatershed.

The *final* step in the watershed-based zoning process involves the adoption of specific resource objectives for each stream and subwatershed. Specific policies and practices on impervious cover limits, stormwater practices, and buffers are then instituted to meet the stream resource objective, and these practices directly applied to future development projects.

Watershed-based zoning should provide managers with greater confidence that resource protection objectives can be met in future development. It also forces local governments to make hard choices about which streams will be fully protected and which will become at least partially degraded. Some environmentalists and regulators will be justifiably concerned about the streams whose quality is explicitly sacrificed under this scheme. However, the explicit stream quality decisions which are at the heart of watershed-based zoning are preferable to the uninformed and random "non-decisions" that are made every day under the present zoning system.

A Cautionary Note

While the research on impervious cover and stream quality is compelling, it is doubtful whether it can serve as the sole foundation for legally defensible zoning and regulatory actions at the current time. One key reason is that the research has not been standardized. Different investigators, for example, have used different methods to define and measure imperviousness. Second, researchers have employed a wide number of techniques to measure stream quality characteristics that are not always comparable with each other. Third, most of the studies have been confined to few ecoregions in the country. Little research has been conducted in the Northeast, Southeast, Midwest, and semi-arid Western regions. Lastly, none of the studies has yet examined the effect of widespread application of stormwater practices on impervious cover/stream quality relationships. Until studies determine how much stormwater practices can "cheat" the impervious cover/stream quality relationship, it can be argued that structural practices alone can compensate for imperviousness effects.

On the positive side, it may be possible for a community to define the impervious cover/stream quality relationship in a short time and at relatively low cost. A suggested protocol for conducting a watershed monitoring study is presented in Table 4. The protocol emphasizes comparative sampling of a large population of urban subwatersheds of different increments of imperviousness (perhaps 20 to 50).

A rapid sampling program collects consistent data on hydrologic, morphologic, water quality, habitat and biodiversity variables within each subwatershed. For comparison purposes, series of undeveloped and undisturbed reference streams are also monitored. The sampling data are then statistically and graphically analyzed to determine the presence of imperviousness/ stream quality relationships.

The protocol can be readily adapted to examine how stormwater practices can shift the stream quality/imperviousness relationship. This is done by adjusting the sampling protocol to select two groups of study subwatersheds: those that are effectively served by stormwater practices and those that are not.

Table 4: Proposed Protocol for Defining Functional Relationships Between Watershed Imperviousness and Stream Quality

- General study design
  A systematic evaluation of stream quality for a population of 20 to 50 small subwatersheds that have different levels of watershed imperviousness. Selected field measurements are collected to represent key hydrological, morphological, water quality, habitat and biodiversity variables within each defined subwatershed. The population of subwatershed data is then statistically analyzed to define functional relationships between stream quality and imperviousness.

- Defining reference streams
  Up to 5 non-urban streams in same geo-hydrological region, preferably fully forested, or at least full riparian forest coverage along same length. Free of confounding NPS sources, imperviousness less than 5%, natural channel and good habitat structure.

- Basic Subwatershed Variables
  Watershed area, standard definition and method to calculate imperviousness, presence/absence of stormwater practices.

- Selecting subwatersheds
  Drainage areas from 100 to 500 acres, known level of imperviousness and age, free of confounding sources (active construction, mining, agriculture, or point sources). Select three random non-overlapping reaches (100 feet) for summer and winter sampling of selected variables in each of five key variables groups:

  1. Hydrology variables: summer dry weather flow, wetted perimeter, cross-sectional area of stream, peak annual storm flow (if gaged).
  2. Channel morphology variables: channel alteration, height, angle and extent of bank erosion, substrate embeddedness, sediment deposition, substrate quality.
  3. Water quality variables: summer water temperature, turbidity, total dissolved solids, substrate fouling index, EP toxicity test, wet weather bacteria, wet weather hydrocarbon.
  4. Habitat Variables: pool- riffle ratio, pool frequency, depth and substrate, habitat complexity, instream cover, riffle substrate quality, riparian vegetative cover, riffle embeddeness
  5. Ecological Variables: fish diversity, macroinvertebrate diversity, index of biological integrity, EPA Rapid Bioassessment Protocol, fish barriers, leaf pack processing rate.

Conclusion

Research has revealed that imperviousness is a powerful and important indicator of future stream quality and that significant degradation occurs at relatively low levels of development. The strong relationship between imperviousness and stream quality presents a serious challenge for urban watershed managers. It underscores the difficulty in maintaining urban stream quality in the face of development.

At the same time, imperviousness represents a common currency that can be measured and managed by planners, engineers and landscape architects alike. It links activities of the individual development site with its cumulative impact at the watershed scale. With further research, impervious cover can serve as an important foundation for more effective land use planning decisions.

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